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# Constructing Restoration Strategies with Availability Risk Constraints

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***Abstract*— System restoration strategies are established and implemented based on the availabilities of components of a system. However, due to lack of accurate information, availabilities of some components may not be known during establishment of restoration strategies after a blackout. In this paper, a novel risk-based methodology is proposed for constructing restoration strategies with stochastic availability constraints for both individual components and restoration paths. Based on a stochastic model of the availability, a multi-stage stochastic optimization model is constructed. A bi-level method is used to solve the proposed model. The established restoration strategy is to achieve a reasonable restoration duration subjects to operating constraints and acceptable risk levels. The proposed risk constraints are introduced into the EPRI's System Restoration Navigator (SRN) with a little modification. Case studies demonstrate the proposed model and methods.**

***Index Terms*-- restoration, availability, risk, bi-level framework**

## I. INTRODUCTION

Power system restoration has been well identified as one of the key components for implementing self-healing in the emerging smart grid. Recent blackouts, such as the 2003 outages in the U.S., the 2006 outage in Europe, and the 2012 one in India are powerful reminders that system restoration requires advanced decision support tools with the ultimate realization of self-healing electric systems. The Electric Power Research Institute (EPRI) of the USA estimated that by minimizing or eliminating interruptions, the self-healing grid could save industrial and residential consumers between $104 billion and $164 billion a year to outages [1]. Unfortunately, very few effective decision support tools are currently available for dispatchers, and restoration plans are still normally established off-line in the context of the individual specific systems.

A restoration strategy is established and implemented based on the availabilities of components of the system. This critical issue has been well identified. For instance, to ensure reliability in system restoration, The North American Electric Reliability Corporation (NERC) has released related standard EOP-005-2 on July 1, 2013[2]. As the first and foremost requirement in this standard, identifications of available blackstart resources, cranking paths have been highlighted in R.1.4-1.6. For instance, R 1.4 requires

*Identification of each Blackstart Resource and its characteristics including but not limited to the following: the name of the Blackstart Resource, location, megawatt and megavar capacity, and type of unit.*

In practice, identification of the status of the collapsed system, components and equipment is also highlighted by the restoration manual of PJM[3], [4] and Hydro-Quebec [5]. For example, PJM Manual 36: System Restoration 3.1.3 requires

*PJM System Operator acts as coordinator and disseminator of information relating to generation and transmission availability.*

Currently, major research on power system restoration addresses the restoration strategies [6], [7] and different constraints on different time-scales [8]-[10]. The restoration strategies are established based on the assumption that information of components' availabilities is acquired.

Establishing restoration strategies subject to the risk due to the availabilities of components is important for implementation of a restoration strategy. Although many advanced technologies have been introduced to system restoration for status awareness, such as PMU[11], [12], due to large geographical distribution and complexity of the blackouts, it is difficult to understand accurate status of the system within very limited time. The availability of each component is described by a probability based on the available information after a blackout and the historical data. The availabilities of components should be integrated into the restoration models and the risk of a restoration strategy should be carefully identified.

The major contribution of this work is to introduce risk constraints associated with availabilities of individual components and transmission paths into power system restoration strategy construction. The restoration problem is modeled as a multi-stage stochastic optimization problem subjects to a set of deterministic operating constraints and

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stochastic risk constraints. A bi-level framework is established to find the restoration sequence of generating units, transmission paths, and operating points of each step. Some algorithms are established to solve the proposed model. The proposed methods are integrated into the EPRI's SRN [1], [6] with a little modification. Case studies compare the different of the restoration strategies with and without risk constraints.

## II. Risk-based Restoration Model

The objective of the proposed restoration model is to provide cranking power and to restart available non-black start units as quickly as possible. Critical loads will be picked up as well. The established restoration strategies will meet the operating constraints as well as the proposed risk constraints. In this model, the availability of each component is described with a probability. Indeed, the current deterministic model, i.e., the availability of each component was known, can be described with the proposed model with probabilities equal to one (the components are available) or zero (the components are unavailable).

A multi-stage model is established as a recursive computation problem as an extension of the deterministic model described in [6]. Let $x_i$ denote the generating unit or critical load restarted at stage $S$, and $\boldsymbol{\theta}_{\mathbf{S}}$ be the set of all restarted generating units and critical loads at stage $S$. Let $f_S(x_i, \boldsymbol{\theta}_{\mathbf{S}})$ be the shortest time to crank all generating units or critical loads within the set $\boldsymbol{\theta}_{\mathbf{S}}$ after stage $S$. The objective function may be written as:

$$f_S(x_i, \boldsymbol{\theta}_{\mathbf{S}}) = \min_{x_i \in \boldsymbol{\theta}_{\mathbf{S}}} \left\{ \Delta t^L_{x_i - x_j} + \Delta t^G_{x_i - x_j} + f_{S+1}(x_j, \boldsymbol{\theta}_{\mathbf{S+1}}) \right\} \tag{1}$$

where $x_j$ is the next generating unit to be restarted in set $\boldsymbol{\theta}_{\mathbf{S+1}}$, $\Delta t^G_{x_i - x_j}$ is the time to crank the generating unit or critical load $x_j$ in $\boldsymbol{\theta}_{\mathbf{S+1}}$, $\Delta t^L_{x_i - x_j}$ is the time to energized associated transmission lines or transformers.

At each stage $S$, the operation constraints are represented as:

$$PF(\boldsymbol{\Omega}_{\mathbf{E(S)}}, \mathbf{P}_{\mathbf{G(S)}}, \mathbf{Q}_{\mathbf{G(S)}}, \mathbf{P}_{\mathbf{CL(S)}}, \mathbf{Q}_{\mathbf{CL(S)}}, \mathbf{P}_{\mathbf{DL(S)}}, \mathbf{Q}_{\mathbf{DL(S)}}) = 0 \tag{2}$$

$$\mathbf{P}_{\boldsymbol{\Pi}} \in \mathbf{FR}_{\mathbf{P}}(\boldsymbol{\Pi}), \mathbf{Q}_{\boldsymbol{\Pi}} \in \mathbf{FR}_{\mathbf{Q}}(\boldsymbol{\Pi}), \boldsymbol{\Pi} = \mathbf{G(S)}, \mathbf{CL(S)}, \text{and } \mathbf{DL(S)} \tag{3}$$

$$\underline{V_B} \le V_B \le \overline{V_B}, \qquad \forall B \in \boldsymbol{\Omega}_{\mathbf{E(S)}} \tag{4}$$

$$\underline{P_L} \le P_L \le \overline{P_L}, \qquad \forall L \in \boldsymbol{\Omega}_{\mathbf{E(S)}} \tag{5}$$

$$\mathrm{Prob}(L_{x_i - x_j}) \ge P \tag{6}$$

where energized block set $\boldsymbol{\Omega}_{\mathbf{E(S)}}$ includes all the energized buses and lines at stage $S$, $\mathbf{P}_{\mathbf{G(S)}}$, $\mathbf{Q}_{\mathbf{G(S)}}$, $\mathbf{P}_{\mathbf{CL(S)}}$, $\mathbf{Q}_{\mathbf{CL(S)}}$, $\mathbf{P}_{\mathbf{DL(S)}}$ and $\mathbf{Q}_{\mathbf{DL(S)}}$ are vectors of real power of generating units, reactive power of generating units, real power of critical loads, reactive power of critical loads, real power of dispatchable loads, and reactive power of dispatchable loads, respectively. $PF(\cdot)$ is the power flow equations. $\mathbf{FR}_{\mathbf{P}}(\boldsymbol{\Pi})$ and $\mathbf{FR}_{\mathbf{Q}}(\boldsymbol{\Pi})$ denote feasible regions of real power and reactive power of the set $\boldsymbol{\Pi}$. $\mathbf{G(S)}$, $\mathbf{CL(S)}$ and $\mathbf{DL(S)}$ are sets of generating units, critical loads and dispatchable loads at stage $S$, respectively. $\boldsymbol{\Pi}$ represents any one of these three sets. $\mathbf{P}_{\boldsymbol{\Pi}}$ and $\mathbf{Q}_{\boldsymbol{\Pi}}$ are real power and reactive power that belong to set $\boldsymbol{\Pi}$, respectively. $V_B$ is the voltage at bus $B$, and $\underline{V_B}, \overline{V_B}$ are the corresponding lower and upper limits. $P_L$ is the real power flow on line $L$, and $\underline{P_L}, \overline{P_L}$ are the corresponding lower and upper limits. In these constraints, (2) represents the power flow equations at each step of restoration; (3) shows that the real power and reactive power of each generating unit, critical load and dispatchable load should stay within the feasible regions at each step; (4) and (5) indicate that the voltage at each bus and power flow through each line should stay within limits.

Especially, (6) provides risk constraints. $\mathrm{Prob}(L_{x_i - x_j})$ is the probability associated with the path $L_{x_i - x_j}$ that connects $x_i$ and $x_j$, $P$ is the lower limit of the probability. Let $L_{x_i - x_j} = \{L_1, L_2, \cdots, L_m\}$, where $L_i$, $i = 1, 2, \cdots, m$, is the lines or transformers within the path between $x_i$ and $x_j$. Denote the availability (probability of $L_i$ is available) of $L_i$ is $A(L_i)$, $\mathrm{Prob}(L_{x_i - x_j})$ can be written as follows:

$$\mathrm{Prob}(L_{x_i - x_j}) = \prod_{i=1}^{m} A(L_i) \tag{7}$$

## III. Bi-level Framewotk for Constrcuting Restoration Strategy with Risk constraints

This section expands the framework established in [6], which was used to establish EPRI's SRN. The risk constraints are introduced into the primary problem of the framework, i.e., finding the sequence of generating units and associated paths. Different from the original framework without risk constraints, the risks associated with availability of a component and a path is included as constraints. As a result, the established restoration strategies are with reasonable restoration duration subject to operating constraints and acceptable risk level. A bi-level method is employed as illustrated in Figure 1.

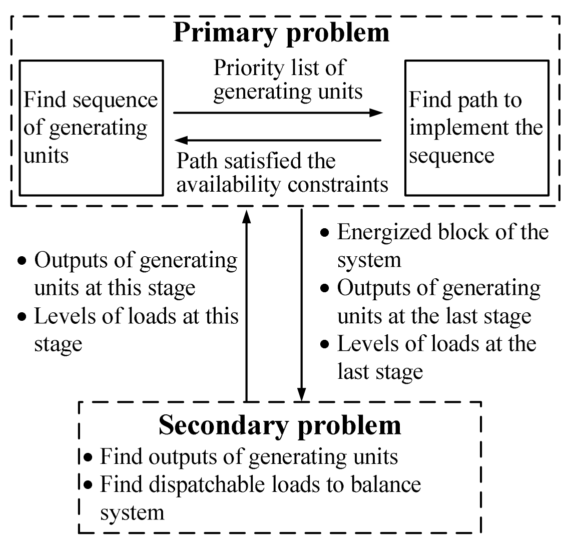

Figure 1. Bi-level framework for the proposed model

The algorithms for the primary problem may be described as follows:

*Step 1: To find the sequence of generating units within the energized blocks*

For a realistic bulk power grid, due to the security consideration, it is impossible to energize a long transmission line for cranking a generating unit instead of cranking a generating unit nearby. In the first step, the generating units near the energized block are identified first according to the Algorithm 1 in paper [6]. For these identified generating units, a priority list will be given based on their capacities and ramping rates. Usually, a generating unit has larger capacity and higher ramping rate is with the higher priority. The output of this step is a priority list generating units within each energized block.

*Step 2: To find a path to crank generating unit satisfying availability constraints*

According to the priority list established in step 1, this step finds the transmission paths. Again, as a critical task, this step is to find an acceptable path within acceptable computing time. The flowchart of the proposed method is described in Figure 2.

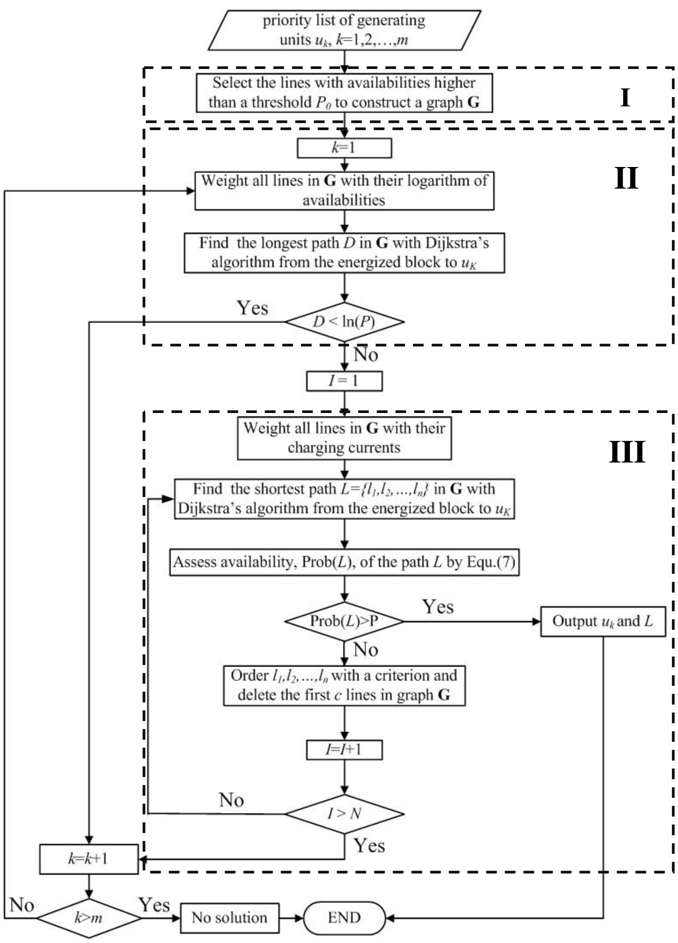


Figure 2. Finding path with availability constraints

The energized block and target generating units ordered with their priorities will be inputted first. The generating units will be checked one by one according to their priorities. The first acceptable generating unit, $u_k$, and associated cranking path will be outputted. The functions of the algorithms described in box I, II, and III are described as follows:

- **Box I**: The transmission lines with lower availabilities are deleted from the graph, and the reliable lines are extracted.

- **Box II**: The path with the largest availability from the energized block to the target generating unit will be found by the Dijkstra's algorithm. If this path's availability is less than the lower limit of the required availability, no acceptable path can be selected. As a result, current target generating unit, $u_k$, has to be deleted from the list at this stage. Since the computational complexity of the Dijkstra's algorithm is $O(|E|+|V|\log|V|)$, where $|E|$ is the number of edges and $|V|$ is the number of vertices of a graph, the shortest (or longest) path can be found within reasonable computing time for a large system.

The availability of a path can be evaluated as follows: let the availability of the line $l_i$ is $A_i(l_i)$ and weight each line with $\ln[A_i(l_i)]$. By using the Dijkstra's algorithm, the longest path, $L=\{l_1, l_2,\ldots,l_n\}$, will be found first. The length, $D$, of path $L$ is:

$$D = \sum_{i=1}^{n} \ln[A_i(l_i)] \tag{8}$$

Since $\sum_{i=1}^{n} \ln[A_i(l_i)] = \ln\left[\prod_{i=1}^{n} A_i(l_i)\right]$, Equ. (8) may be written as:

$$D = \ln\left[\prod_{i=1}^{n} A_i(l_i)\right] \tag{9}$$

where $\prod_{i=1}^{n} A_i(l_i)$ is the availability of the path $L$. Therefore, $D < \ln(P)$ indicates $\prod_{i=1}^{n} A_i(l_i) < P$.

- **Box III**: The path from the energized block to a target generating unit, $u_k$, with minimal total charging current subject to acceptable availability will be identified.

Each line, $l_i$, in the system is weighted with its charging current, $C_i(l_i)$, to limit the steady-state overvoltage. After identifying the shortest path with the Dijkstra's algorithm, availability of this path will be checked. If the path's available is greater than a threshold, the target generating units, $u_k$, and path $L$ will be outputted. Otherwise, the lines in the path $L$ are ordered with the following criterion.

$$\lambda_i(l_i) = \frac{A_i(l_i)}{C_i(l_i)} \tag{10}$$

In the path $L$, a line with the smallest availability $A_i(l_i)$ and largest charging current $C_i(l_i)$ will be deleted first. The Dijkstra's algorithm will be employed again to find the path in the updated graph.

The algorithms for the secondary problem are to find the suitable operating point for the identified block. Since the components of the block is given by the primary problem. The secondary problem solves an optimal power flow model with ramping rate constraints. The methods described in [6] will be used in this work.

By this proposed framework, the restoration strategy will be established step by step. The operating constraints, such as MVA rating of each line, voltage level of each bus, ramping rate of each generating units, as well as the availability constraints of the system components will be satisfied.

## IV. ILLUSTRATIVE EXAMPLE

The proposed methods are demonstrates in this section. The benchmark system without risk constraints is solved by EPRI's SRN. The proposed methods are employed to extend SRN for establishing restoration strategies with availability constraints of components and paths. The restoration sequences and durations under different scenarios are solved. Simulation results show that compared with the system without risk constraints, the restoration durations of the systems with risk constraints will be extended. However, the components and paths with low availabilities are avoided to be involved during system restoration. As a result, the risk level of the established restoration strategies is limited. In these case studies, the availability of each component is given. In a realistic blackout, availabilities may be estimated with the historical data and real-time blackout scenarios.

The following three examples are: part A gives the benchmark system, i.e., the system restoration without available constraints. Part B generates a restoration strategy for the system with availability constraints on some components. Part C establishes a restoration strategy for the system with availability constraints on restoration paths. The results of part B and C are compared with the benchmark system described in part A.

### A. *Benchmark system*

A built-in 23-bus testing system of PSS/E is used to illustrate the proposed methods. This test system includes 6 generators, 1 critical load on bus, 6 dispatchable loads, and 34 branches. Two generators on bus 101 and 102 are Blackstart generators. The topology of the system is illustrated as Fig. 3. The system data can be found in the manual of PSS/E. the characteristics of generating units are listed in Table I.

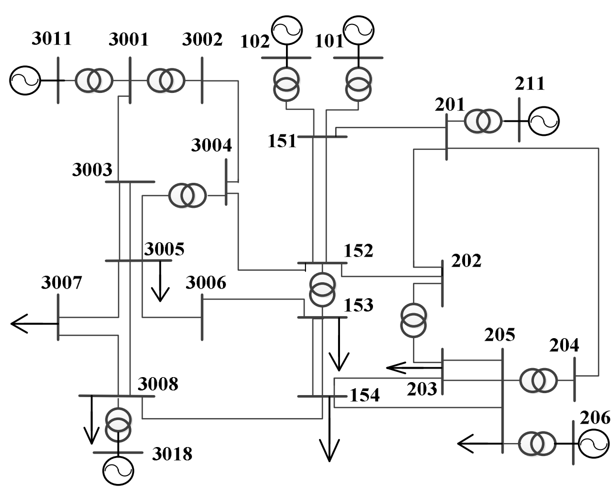


Fig 3. Topology of the test system

TABLE I. CHARACTERISTICS OF GENERATING UNITS

| Bus | BS /NBS | Capacity (MW) | Startup Requirement (MW) | Ramping Rate (MW/hr) | Time to Parallel (hr) |
|---|---|---|---|---|---|
| 101 | BS | 810 | 0.0 | 600 | 0.00 |
| 102 | BS | 810 | 60.0 | 480 | 0.50 |
| 206 | NBS | 900 | 60.0 | 480 | 0.25 |
| 211 | NBS | 616 | 60.0 | 288 | 0.10 |
| 3011 | NBS | 900 | 80.0 | 490 | 0.75 |
| 3018 | NBS | 117 | 0.0 | 40 | 0.00 |

Without risk constraints, i.e., all components are available, the restoration process can be established by SRN as Table II. This process is used as the benchmark for the following two scenarios with risk constraints.

TABLE II. RESTORATION PROCESS OF THE BENCHMARK SYSTEM

| **Step** | **Path** | **Cranking Unit** | **Time (mins)** |
|---|---|---|---|
| 0 | - | 101, 102 | 0 |
| 1 | 151-101, 151-102, 151-201, 201-211 | 211 | 40.00 |
| 2 | 201-204, 204-205, 205-206 | 206 | 55.00 |
| 3 | 205-154, 154-153, 153-3006, 3006-3005, 3005-3008, 3008-3018 | 3018 | 85.00 |
| 4 | 3005-3003, 3003-3001, 3001-3011 | 3011 | 100.00 |
| 5 | - | 3008 (critical load) | 106.00 |

### B. *System with low availability components*

This case illustrates the system with some components' availabilities are less than the threshold $P_0$.

Let the availabilities of two transformers, i.e., 204-205 and 202-203, equal to 0.9. The threshold of availability $P_0 = 0.95$. Other lines availabilities are all 1. By the algorithms proposed in this paper as described in Figure 2(box I and box II), the restoration process is summarized in Table III.

TABLE III. RESTORATION PROCESS OF CASE B

| **Step** | **Path** | **Cranking Unit** | **Time (mins)** |
|---|---|---|---|
| 0 | - | 101, 102 | 0 |
| 1 | 151-101, 151-102, 151-152, 152-153,152-3004, 3004-3005, 3008-3018 | 3018 | 55.00 |
| 2 | 153-154, 154-205, 205-206 | 206 | 100.00 |
| 3 | 151-201, 201-211 | 211 | 122.00 |
| 4 | 3005-3003, 3003-3001, 3001-3011 | 3011 | 150.00 |
| 5 | - | 3008 (critical load) | 179.00 |

Compared with the benchmark system, the restoration duration increases significantly with a different path since two components are unavailable. Transformers 204-205 and 202-203, which are with low availabilities, are not utilized during the system restoration. As a result, the risk for implementing this restoration strategy can be limited.

### C. *System with low availability paths*

This case demonstrates that some components with low availabilities. Although the availability of each component is greater than $P_0$, it may result in low availability of a restoration path.

In this case, assume the threshold of a path's availability $P$ is 0.95. The availabilities of components, which are less than 1, are summarized in Table IV. The rest component availabilities in this system are all equal to 1.

TABLE IV. AVAILABILITY OF THE SOME LINES AND TRANSFORMERS

| Line /Transformer | Availability | Line /Transformer | Availability |
|---|---|---|---|
| 203-205 | 0.989 | 205-154 | 0.965 |
| 203-154 | 0.973 | 154-153 | 0.975 |
| 154-3008 | 0.988 | 3008-3018 | 0.999 |
| 3008-3005 | 0.995 | 3005-3006 | 0.990 |
| 3006-153 | 0.990 | 205-206 | 0.999 |

By the proposed method, the restoration process is illustrated in Table V.

TABLE V. RESTORATION PROCESS OF CASE C

| Step | Path | Cranking Unit | Time (mins) |
|---|---|---|---|
| 0 | - | 101, 102 | 0 |
| 1 | 151-101, 151-102, 151-201, 201-211 | 211 | 40.00 |
| 2 | 201-204, 204-205, 205-206 | 206 | 55.00 |
| 3 | 205-203, 203-154, 154-3008, 3008-3018 | 3018 | 75.00 |
| 4 | 3008-3005, 3005-3003, 3003-3001, 3001-3011 | 3011 | 95.00 |
| 5 | 3005-3006, 3006-153 | 3008 (critical load) | 115.00 |

In this case, step 0~ step 2 are the same as the benchmark system since two systems are with the same parameters. In Step 3, the availability of the original path as shown in Table II is 0.92, which is less than the acceptable level, 0.95. Based on the algorithm described in box III of the Fig. 2, the paths with lower availabilities and higher charging currents, i.e., 205-154 and 154-153, were deleted in the graph. By the Dijkstra's algorithm, the new path is 205-203, 203-154, 154-3008, 3008-3018, with the availability as 0.95.

The results listed in Table V also indicate that with the proposed method, the proposed methods with accurate information will establish the same restoration strategy as the deterministic algorithm. With the risk associated with availability, since more constraints are considered, duration of the restoration duration might be extended and risk levels of the established strategies are limited.

## V. CONCLUSIONS

This paper proposes a novel method to establish power system restoration strategy subject to operating constraints and availability risk constraints. Since accurate system information might not be fully available after a blackout. The risk associated with the inaccurate information should be carefully considered during constructing a restoration strategy. The major work of this paper is as follows:

(1)A stochastic availability model of each component is established first. The restoration problem is modeled as a multi-stage stochastic optimization problem. Expect for the regular operating constraints, the availabilities of restoration path and each component are involved as constraints.

(2) A bi-level framework and associated algorithms are proposed to solve the restoration problem with operation and risk constraints. The proposed method is also integrated into EPRI's SRN with new constraints.

(3) The proposed methods are implemented and tested. The restoration strategies for a system without availability constraints, with component's availability constraints, and with restoration path's availability constraints, are compared.

(4) Compared with the restoration strategy without availability constraints, the restoration duration may be extended with availability constraints due to more constraints are involved. However, the risk level of the restoration strategies can be limited with the proposed method. Furthermore, the proposed models can also be used the solved the original problem, i.e., establishing restoration strategies without availability constraints.

## REFERENCES


[1] C.-C. Liu, W. Sun, Y. Hou, and S. Liu. Putting into Practice the Dream of a Self-healing Smart Grid, Sept. 2011 [Online]. Available: http://smartgrid.ieee.org/newsletter/september-2011/53-putting-into-practice-the-dream-of-a-self-healing-smart-grid

[2] http://www.nerc.com.

[3] R. J. Kafka, "Review of PJM restoration practices and NERC restoration standards," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-5.

[4] PJM Manual 36: System Restoration. http://www.pjm.com/~/media/documents/manuals/m36.ashx.

[5] F. Levesque, S. T. Phan, A. Dumas, and M. Boisvert, "Restoration plan — The Hydro-Québec experience," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-6.

[6] Y. Hou, C. C. Liu, K. Sun, P. Zhang, S. Liu, and D. Mizumura, "Computation of Milestones for Decision Support During System Restoration," Power Systems, IEEE Transactions on, vol. 26, pp. 1399-1409, 2011.

[7] W. Sun, C.-C. Liu, and R. F. Chu, "Optimal Generator Start-Up Strategy for Power System Restoration," in Intelligent System Applications to Power Systems, 2009. ISAP '09. 15th International Conference on, 2009, pp. 1-7.

[8] M. M. Adibi and L. H. Fink, "Overcoming restoration challenges associated with major power system disturbances - Restoration from cascading failures," Power and Energy Magazine, IEEE, vol. 4, pp. 68-77, 2006.

[9] M. M. Adibi and N. Martins, "Power system restoration dynamics issues," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-8.

[10]M. M. Adibi, Power System Restoration : Methodologies & Implementation Strategies New York: IEEE PES Press 2000.

[11]S. Kolluri, S. Mandal, F. Galvan, and M. Thomas, "Island formation in entergy power grid during Hurricane Gustav," in Power & Energy Society General Meeting, 2009. PES '09. IEEE, 2009, pp. 1-5.

[12]Y. Hou, S. Liu, and Z. Qin, "Construction of System Restoration Strategy with PMU Measurements," Energy Procedia, vol. 12, pp. 377-386, 2011